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Review of trend detection methods and their application to detect temperature changes in India

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SUMMARY

Present study performs the spatial and temporal trend analysis of annual, monthly and seasonal maximum and minimum temperatures (t_{max}, t_{min}) in India. Recent trends in annual, monthly, winter, pre-monsoon, monsoon and post-monsoon extreme temperatures (t_{max}, t_{min}) have been analyzed for three time slots viz. 1901–2003, 1948–2003 and 1970–2003. For this purpose, time series of extreme temperatures of India as a whole and seven homogeneous regions, viz. Western Himalaya (WH), Northwest (NW), Northeast (NE), North Central (NC), East coast (EC), West coast (WC) and Interior Peninsula (IP) are considered. Rigorous trend detection analysis has been exercised using variety of non-parametric methods which consider the effect of serial correlation during analysis. During the last three decades minimum temperature trend is present in All India as well as in all temperature homogeneous regions of India either at annual or at any seasonal level (winter, pre-monsoon, monsoon, post-monsoon). Results agree with the earlier observation that the trend in minimum temperature is significant in the last three decades over India (Kothawale et al., 2010). Sequential MK test reveals that most of the trend both in maximum and minimum temperature began after 1970 either in annual or seasonal levels.

1. Introduction

A number of studies were partially concentrated for analyzing the impact of climate change and variability on different components of hydrological cycle. In the most recent studies it is observed that significant warming in the second half of the 20th century resulted in a drastic change in the hydrology of an agricultural based country like India. Magnitude and trend of warming of India during the last century over Indian continent is matching with the global condition (Pant and Rupa Kumar, 1997). Drastic change in the hydrological parameters such as precipitation, evaporation and streamflow is influencing the flow regimes substantially. Hydrologic variables (evaporation, precipitation, runoff etc.) are directly or indirectly dependent on atmospheric variables (pressure, humidity, temperature, precipitable water etc.). It is necessary to establish the relations between atmospheric and hydrological variables, which can provide useful insights into the possible changes in hydrology of a region and also can aid in decision-making in water resources management related issues.

Among the various dominant atmospheric variables, temperature has a significant and direct influence on almost all hydrological variables. As the temperature increases, the relative humidity usually decreases and vice versa. Evapotranspiration is affected by weather parameters and crop growth dynamics. Increase in temperature leads to increase in demand of crop water and decrease in its supply. Spatial pattern, temporal pattern and variability of surface temperature plays a vital role in modelling miscellaneous processes in hydrology, climatology, agriculture, environmental engineering, and forestry both at local and global levels. (Anandhi et al., 2009; Tabari et al., 2011).

From the year 1970 onwards, considerable literature concerning the trend detection techniques is available in environmental and hydrological field. Some of those studies are: Sen's nonparametric slope estimator (Sen, 1968), least squares linear regression for the detection of trends in time series of hydrological variables (Haan, 1977), work concerning the Spearman rank correlation test (Lettenmaier, 1976) and seasonal Mann–Kendall test (Hirsch et al., 1982; Hirsch and Slack, 1984). Due to the perceptible increase in global average surface temperature, there is a drastic change in hydrologic parameters such as evaporation and precipitation resulting in cumulative impact on river flow regimes. A number of studies were attempted in basin, regional and country wide levels for trend detection such as Burn and Hag Elnur (2002), Xiong and Shenglian (2004), Zhang et al. (2001).

A critical review of the studies (Khaliq et al., 2009; Kundzewicz and Robson, 2004; Reeves et al., 2007) indicated that parametric, non-parametric, Bayesian, time series and nonparametric methods with resampling approaches were mainly used in trend detection studies for different hydrologic and climatic variables.

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2. Statistical approaches for trend detection

1. Slope based tests, namely least squares linear regression (referred as LR henceforth) and Sen's robust slope estimator (referred as SS) were used for trend detection.
2. Rank-based tests, namely Mann–Kendall (referred as MK) and Spearman rank correlation (referred as SRC) were also used for trend detection.

These are commonly used statistical tests for identifying hydrological trends in literature. LR is a parametric approach and needs to satisfy both distributional and independent assumptions, whereas rank based methods are nonparametric and need to satisfy the second assumption only. SS is not strictly a statistical test. In order to find out the upper and lower limits of the test statistics, resampling approach needs to be adopted.

3. Statistical approaches for trend detection, considering serial correlation effect

Improper assumption of independent observations could result in erroneous conclusions. So the effect of serial correlation should be considered in case of hydrologic and climatic variables. The most employed statistical approaches which consider the effect of serial correlation are: the pre-whitening (referred as PW), trend-free pre-whitening (referred as TFPW), variance correction approach (VC) by Hamed and Rao (1998) with MK test (referred as MK-CF1), Yue and Wang (2004) with MK test (referred as MK-CF2);block resampling techniques, e.g. the block bootstrap (BBS) with MK test (referred to BBS-MK) and BBS with SR (referred as BBS-SR) Noguchi et al. (2011).

The PW and TFPW approaches are based on the assumption of AR(1) process, which is undoubtedly a debatable assumption as hydrological variables could be better represented by some other time series models.

4. Other approaches for trend detection

Parametric technique, student *t*-test, which is based on the difference between sample means can be used for testing a signal change i.e. step change (not gradual). With known mathematical model of data, Bayesian analysis can be used for signal change testing. In case of real application, distributional assumption of parametric test cannot always be satisfied. Substitute to the paired Student's *t*-test is the Wilcoxon signed-rank test which is a nonparametric method. The main limitation of this test is that it can detect only one single change point whereas the Sequential Mann–Kendall test and Cumulative Sum (CUSUM) are nonparametric tests particularly useful for sequential step change analysis. Cumulative Sum test is based on the cumulative sum charts and is used to detect the sequential changes in one or more variables with many advantages such as ability to detect unusual patterns, simplicity, and better graphical representation of results. Application of CUSUM in onset detection, in seismic signal processing, in detection of change in mechanical system and in faulty detection is found in literature (Alippi and Roveri, 2006). Parameters are to be decided a priori at the design stage for trend detection analysis as in CUSUM test in which thresholds, which are used to observe the changes in the statistical behavior and in MK test the level of significance of the test.

4.1. Adaptive Cumulative Sum (CUSUM) (Alippi and Roveri, 2006)

This is an extension of the CUSUM test, which allows the test parameters to be configured automatically during the process itself. This method is effective when the correct prior information about the parameter and the envisaged signal probability distribution function are unknown.

4.2. Innovative trend analysis approach (Sen, 2012)

This approach is on the basis of sub section time series plot on a Cartesian coordinate system. This shows whether any increasing or decreasing trend exists by finding upper and lower triangle with respect to 45° trend free line. If the 1:1 line plots appear along a straight line parallel to 1:1 line, then the trend is monotonic, otherwise it is a combination of various trends or trend free portions. Irrespective of distributional assumption, correlation structure and sample size, this method seems to be effectual. PW or TFPW application is not needed a priori, like in other classical methods for trend detection study. This method is validated through extensive Monte Carlo simulation and then applied for two annual runoff and one precipitation series from Turkey in addition to annual flows of the Danube River. In the present study this approach is adopted at different temporal and spatial scales.

4.3. Singular spectrum analysis (referred as SSA) (Hassani, 2007)

This is a novel approach and is useful in solving many tasks such as change point detection, find structure in short time series, simultaneous extraction of cycles with small and large periods as well as complex trend and periodicities, extraction of seasonality and periodicity with different amplitude and trend detection in different resolutions.

In SSA, confidence interval can be found out with two approaches, empirical and the bootstrap methods. The SSA technique consists of decomposition and reconstruction stages. Both these stages again consist of two steps. First stage-first step: embedding (transfers a one-dimensional time series into the multi-dimensional series), first stage-second step: singular value decomposition of the trajectory matrix and represent it as a sum of rank-one bi-orthogonal elementary matrices; second stage-first step: grouping (identifying signal component and noise), second stage-second step: diagonal averaging (using grouped eigentriples to reconstruct the new series without noise). Eigenvalue, eigenvector and principal component are known as eigentriple. Typically, the leading eigentriples describe the general characteristics of the time series. The main concept of SSA is separability (how well different components can be separated from each other). Auxiliary information can be considered as a bridge between decomposition and reconstruction and help in choosing the proper parameters for building a proper model. In a time series, trend is the slowly varying component. In practice one or more of the leading eigenvectors will be slowly varying as well. Thus slowly varying eigenvectors should be found out for trend detection in time series. One dimensional plots of eigenvector can give an idea on the variation of trend.

To observe the changes in any time series (hydrological or climatological records), it is primarily necessary to check the quality as well as length of the series due to their considerable significance in such analysis. Erroneous and short length data records can lead to spurious inferences in detecting trends. Consideration of high quality data with good record is essential for any analysis related to observation of changes in time series. Data obtained using remote sensing from satellites generally have very short record lengths and very voluminous to be processed. The most commonly used tests to observe changes generally consider one of the following factors.

- General change in distribution.
- Trend or gradual change in the mean or median of a series.
- Step changes in the mean or median of a series.

If there is presence of trend in a time series, then the distribution tests are not much useful and it is better to check the trend instead of distribution (Kundzewicz and Robson, 2000).

The power of the test is defined as the probability of correctly detecting the trend when it is present. There are possibilities of two types of error in the test result; type I error: null hypothesis is incorrectly rejected and type II error: null hypothesis is accepted when the alternative hypothesis is true. Significance level expresses the probability of type-I error, while low type II error indicates more powerful test. Power of any test is found out by counting the number of the rejections of the null hypothesis of no trend.

While conducting any statistical test (to detect trend) proper care should be taken for correct interpretation of data and test assumptions. More than one test should be used to draw a conclusion because each statistical test addresses specific questions. Finally from the entire statistical test, the proof only can be obtained and not evidence. Sometimes test sign may be the indication a wrong reason.

Power of the MK test is directly proportional to the trend magnitude, sample size and indirectly proportional to coefficient of variation (Yue et al., 2002a). PW used to remove the effect of serial correlation resulting in reduction of power in trend detection test.

Yue et al. (2002b) suggested a procedure which is an improvement to PW known as TFPW to find out the trend in serially correlated data. They found that TFPW approach has more power than PW and VC approaches. Yue and Pilon (2004) compared the powers of the parametric *t*-test, MK test, bootstrap-based *t*-test and MK, and concluded that the MK and bootstrap-based MK tests have the same power, as long as the data are uncorrelated.

Bayazit and Önöz (2007) found that the real power loss due to PW is defined as the ratio of the power of a correlated series with application of PW to without PW, when there is no serial correlation. For large samples size $\geqslant 50$ and trends magnitude $\geqslant 0.01$, PW of the series is not needed as there will be negligible effect of serial correlation on type–I error and could result in significant power loss of test. Khaliq et al. (2009) also agreed with this statement. Hamed (2009) suggested that if PW is a major concern, then increased significance level can be useful in solving the issue. The PW and TFPW approaches modify the data structure of the original time series with serially correlated data points and are valid with the assumption of AR(1) process.

Khaliq et al. (2009) applied the modified MK tests with PW, VC approach, and BBS-MK to annual mean daily flows. In case of BBS-MK, the optimized block length is found to be $k + 1$, where $r(k)$ is the smallest significant auto correlation and k is the lag. MK test modified with PW and BBS is having less power in the presence of serial correlation while TFPW approach is inappropriate in preserving the nominal significance level. Finally they have recommended BBS-MK and VC approaches as proper trend detection techniques.

Önöz and Bayazit (2011) found out the type-I and type-II errors for block bootstrapped base MK test. Type-I error is a function of sample size and, auto correlation coefficient. Properly selected block length in the block bootstrapping approach can minimize the type-I error. Power of BBS-MK test is comparable to other modified MK tests.

Hingane et al. (1985) reported that in India during 1901–1982 the mean annual temperature increased by about 0.4 °C/100 yr. The loss in temperature between day time high temperature and night time low temperature is decreasing in the second half of the 20th century (Easterling et al., 1997). Mean air temperature during 1881–1997 is showing an upward trend at the rate of 0.57 °C/100 yr (Pant and Rupa Kumar, 1997). In the first half of the 20th century warming over India is strictly brought by maximum temperature (Kothawale and Rupa Kumar, 2005). During the last three decades trend in minimum temperature is substantial as compared to maximum temperature, regardless of considerable reduction in the monthly mean surface reaching solar radiation (Kumari et al., 2007). Kothawale et al. (2010) examined pre-monsoon daily temperature extremes over India and found that there is absence of substantial change in day-to-day fluctuations of pre-monsoon temperature extremes. Trend magnitude and statistical significance were assessed by linear regressed fitted line and Mann Kendall rank statistics respectively. Basistha et al. (2009) attempted to explore changes in rainfall pattern in the Indian Himalayas during 20th century using 80-year data from 30 rain gauge stations. Applying Modified Mann–Kendall test (MMK) it is concluded that, there is an increasing trend up to 1964, followed by a decreasing trend in 1965–1980.

Trend detection studies concerning India may have the following limitations.

- A number of trend detection studies were conducted in terms of rainfall, but very few on temperatures (Basistha et al., 2009; Parthasarathy, 1984; Parthasarathy et al., 1991; Parthasarathy and Dhar, 1976; Parthasarathy and Mooley, 1978).
- Most of the trend detection studies have analyzed using commonly used techniques such as least square regression (Parametric test) and Mann–Kendall test (non-parametric test with independent observations assumption).
- In most of the studies, proper care was not taken for the independent assumption, which is not valid in the case of hydrologic variables. If correlation between consecutive observations is not taken into consideration, it can lead to erroneous conclusions.
- In many studies it was suggested (Khaliq et al., 2009; Kundzewicz and Robson, 2004; Önöz and Bayazit, 2011) to adopt more than one method for identifying temporal change signals satisfactorily. This is missing in almost all the studies concerning the signature of climate change over India.
- Very few studies are available based on the study area of temperature homogeneous region (Kothawale et al., 2010). Detailed analysis in this study area will give a broad overview of changing climate and its effect in the different parts of India. This will be helpful for providing strong evidence to detection and attribution studies in hydroclimatological perspective as well as forecasting studies.
- Consideration of temperature trend in All India as well as in temperature homogeneous regions at monthly, seasonal viz. winter, per-monsoon, monsoon, post-monsoon and annual level was rarely studied. By considering different intervals in a year, dramatic changes in trend characteristics can be observed/verified.
- No studies at India level appear concerned with the starting time of trends with a formal trend detection technique like sequential Mann Kendall test (SQMK).

In this study a variety of approaches are being employed to check short term, long term, gradual, abrupt changes, beginning of trend and change in trend over time. This analysis will be helpful in inferring the relation of temperature with evaporation and precipitation for future projection. From different literature studies, it is observed that none of the methods are perfect as all the statistical approaches give only proof but not evidence. To cover this lacuna this detailed trend detection study over India and in all temperature homogeneous regions of India is being conducted, applying the following methods.

Following trend detection methods are employed in the present study.

- Least squares linear regression (LR) test.
- Mann–Kendall test (MK).
- Spearman rank correlation (SRC) test.
- Sen's slope (SS).
- Trend-free pre-whitening (TFPW) with MK.
- Variance correction (VC) approach with MK test based on Hamed and Rao (1998) (MK-CF1).
- Variance correction (VC) approach with MK test based on Yue and Wang (2004) (MK-CF2).
- Block bootstrap (BBS) with MK i.e. BBS-MK.
- Block bootstrap (BBS) with SR i.e. BBS-SR.
- Sequential Mann–Kendall test (SQMK).
- Innovative trend analysis approach based on Sen (2012).

These methods are briefly explained in this section.

5. Least squares linear regression (LR) test

LR test is a parametric test. Before application of this test, normality check should be done as, hydrologic and climatic data are skewed most of the time. This test used to describe the presence of linear trend in time series (Haan, 1977). The test statistic T is defined as

$$T = \frac{\hat{b}}{se(\hat{b})}$$

where $\hat{b}$ is the estimated slope of the regression line between observed values and time and $se(\hat{b})$ stands for the stand error of estimated slope. Test statistic T follows a student's t-distribution with $n-2$ degree of freedom, where n is the length of sample. The null hypothesis of slope zero will be rejected when the test statistic T value is greater than the critical value $t_{\alpha/2}$ with α significance level.

6. Mann–Kendall test

The MK test is a non-parametric rank based test (Kendall, 1975; Mann, 1945).Test statistic S is defined as follows.

$$S = \sum_{i=2}^{n}\sum_{j=1}^{i-1}\text{sign}(x_i - x_j)$$

where n is the length of the data series x_i and x_j are the sequential data in the series and

$$\text{sign}(x_i - x_j) = \begin{cases} -1 & \text{for } (x_i - x_j) < 0 \\ 0 & \text{for } (x_i - x_j) = 0 \\ 1 & \text{for } (x_i - x_j) > 0 \end{cases}$$

$$E[S] = 0$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{P-1}^{q} t_p(t_p-1)(2t_p+5)}{18}$$

where t_p is the number of ties for the pth value and q is the number of tied values. The second term in the variance formula is for tied censored data. Standardized test statistic Z is computed by

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases}$$

To test for monotonic trend at α significance level, the null hypothesis of no trend is rejected if the absolute value of standardized test statistic Z is greater than $Z_{1-\alpha/2}$ obtained from the standard normal cumulative distribution tables.

7. Spearman rank correlation (SRC) test

In SRC test, the test statistic is based on the Spearman rank correlation coefficient r_{SRC}.

$$r_{SRC} = 1 - \left\{ \frac{6\sum_{i-1}^{N} d_i^2}{n(n^2-1)} \right\}$$

where i represents the chronological order and n is the total number of data points in the series. $d_i = RX_i - RY_i$, where RX_i is the rank of variable X_i, which is the chronological order of observations. The series of observations Y_i is transformed to its rank equivalent RY_i by assigning the chronological order in the ranked series. For the ties, average rank will be considered. The test statistic t_{SRC} is given by

$$t_{SRC} = r_{SRC}\sqrt{\frac{(n-2)}{(1-r_{SRC}^2)}}$$

The null hypothesis implying no trend will not be rejected if $t_{v,\alpha/2} < t_{SRC} < t_{v,1-\alpha/2}$.Where test statistic t_{SRC} follows a student's t-distribution with degrees of freedom $v = n-2$ and significance level α.

8. Sen's slope (SS)

Using the method of Sen (1968), the magnitude of the slope can be obtained as follows

$$b_{Sen} = \text{Median}\left[\frac{Y_i - Y_j}{(i-j)}\right] \qquad \text{for all } j < i$$

where Y_i and Y_j are data at time points i and j, respectively. If the total number of data points in the series is n, then there will be $\frac{n(n-1)}{2}$ slope estimates and the test statistic b_{Sen} is the median of all slope estimates. Positive and negative sign of test statistics indicate increasing trend and decreasing trends respectively.

9. Trend-free pre-whitening (TFPW) with MK test (Yue et al., 2002b)

1. Estimate the slope of the time series using Sen's slope method.
2. Detrend the time series (with the assumption of linear trend, as this approach works with the assumption of AR(1) process). Find the lag-1 correlation coefficient from the detrended series with some defined significance level α.
3. If lag-1 correlation coefficient is significant with the considered significance level, then the MK test will apply to the detrended pre-whitened series recombined with the estimated slope of trend using SS test, else apply MK test to the original series.

10. Variance correction (VC) approach

Basically n serially correlated observations contain the same information as n^*. Effective sample size n^* is always less than the original sample size. Presence of positive (negative) serial correlation results in increase (decrease) in the variance of Mann–Kendall test statistic S. Due to this problem, the variance correction approach was proposed by Hamed and Rao (1998) and Yue and Wang (2004).Later Lettenmaier (1976) proposed variance correction approach for the SRC test. The modified variance of the MK test statistic is given by

$$Var(S)* = CF * Var(S)$$

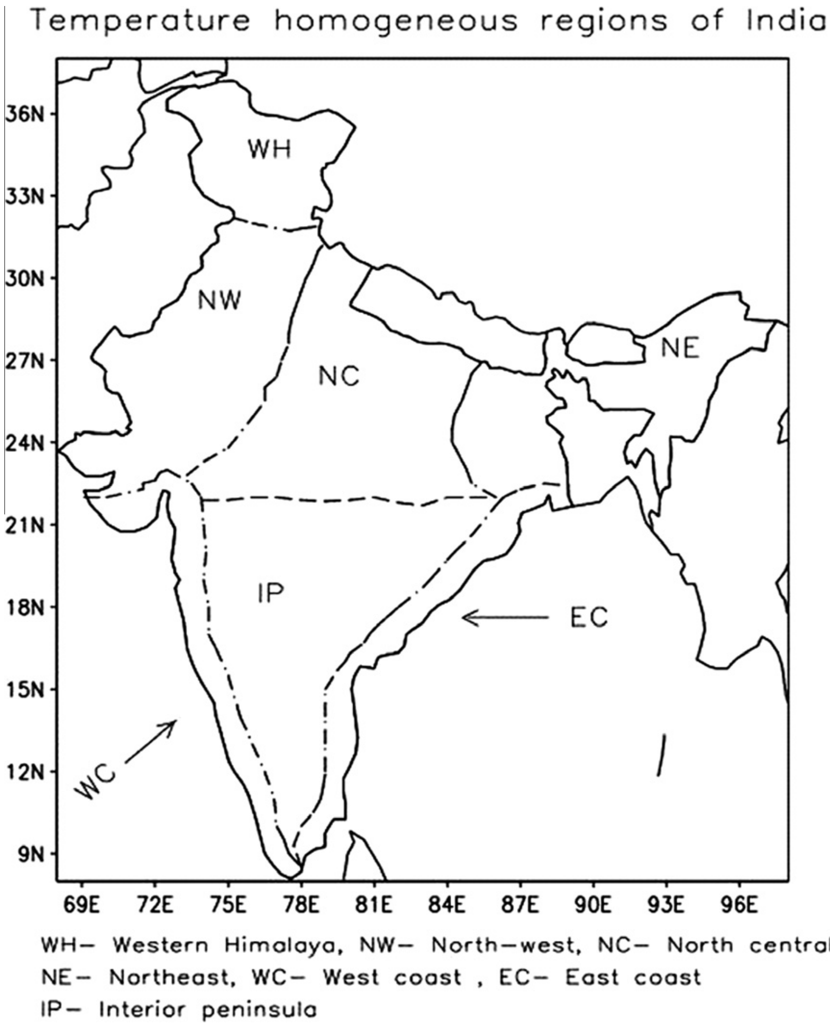

Fig. 1. Temperature homogeneous regions used for the study.

where CF is correction factor. CFs proposed by Hamed and Rao (1998) and Yue and Wang (2004) are denoted as CF_1 and CF_2 respectively.

$$CF_1 = 1 + \frac{2}{n(n-1)(n-2)} \sum_{k=1}^{n-1} (n-k)(n-k-1)(n-k-2) r_k^R$$

$$CF_2 = 1 + 2\sum_{k=1}^{n-1} \left(1 - \frac{k}{n}\right) r_k$$

where r_k and r_k^R are the lag-k serial correlation coefficients of data and ranks of data respectively and n is the total length of the series. MK test with the CF_1 and CF_2 are respectively referred as MK-CF_1 and MK-CF_2. In this study these tests are applied with the assumption of AR (1), e.g. by taking $r_k = r_1^{|k|}$ for the MK-CF_2 test.

11. Block bootstrapping (BBS) with MK and SR

To preserve the effect of serial correlation in a time series while resampling it, Kundzewicz and Robson (2000) suggested a block resampling approach. The original data is resampled with respect to a predefined block length for a large number of times. This block resampling approach is helpful in finding out significance of observed test statistic, which is very important for trend detection study. Steps for BBS approach are given below.

1. Estimate the test statistic of the selected test to identify trend (At present MK, SR).
2. Estimate the least significant serial correlation with respect to lag (k) for the considered series. Optimized block length (Khaliq et al., 2009) will be considered as $k + 1$.
3. Resample the original series in blocks to preserve the serial correlation. In the present study, resampling is done without replacement for 10,000 times. Resampling should be at least done for 2000 times.
4. From each resampled series, find out the test statistic derived in the first step. Then develop a distribution using all the test statistics derived from resampled series. If the original test statistic lies within the upper and lower bounds of the simulated distribution, then the test statistic is considered to be significant. Unequal block size is not a problem. In the present study equal block length is considered for convenience, except the last one.

12. SQMK

To observe the beginning as well as changes over time of any trend is important in any trend detection study. Sequential MK (SQMK) test (Modarres and Sarhadi, 2009; Sneyers, 1990), which is progressive and retrograde analyses of the Mann–Kendall test, will produce sequential values $u(t)$ and $u'(t)$ respectively. These are standardized variables with zero mean and unit standard devi-

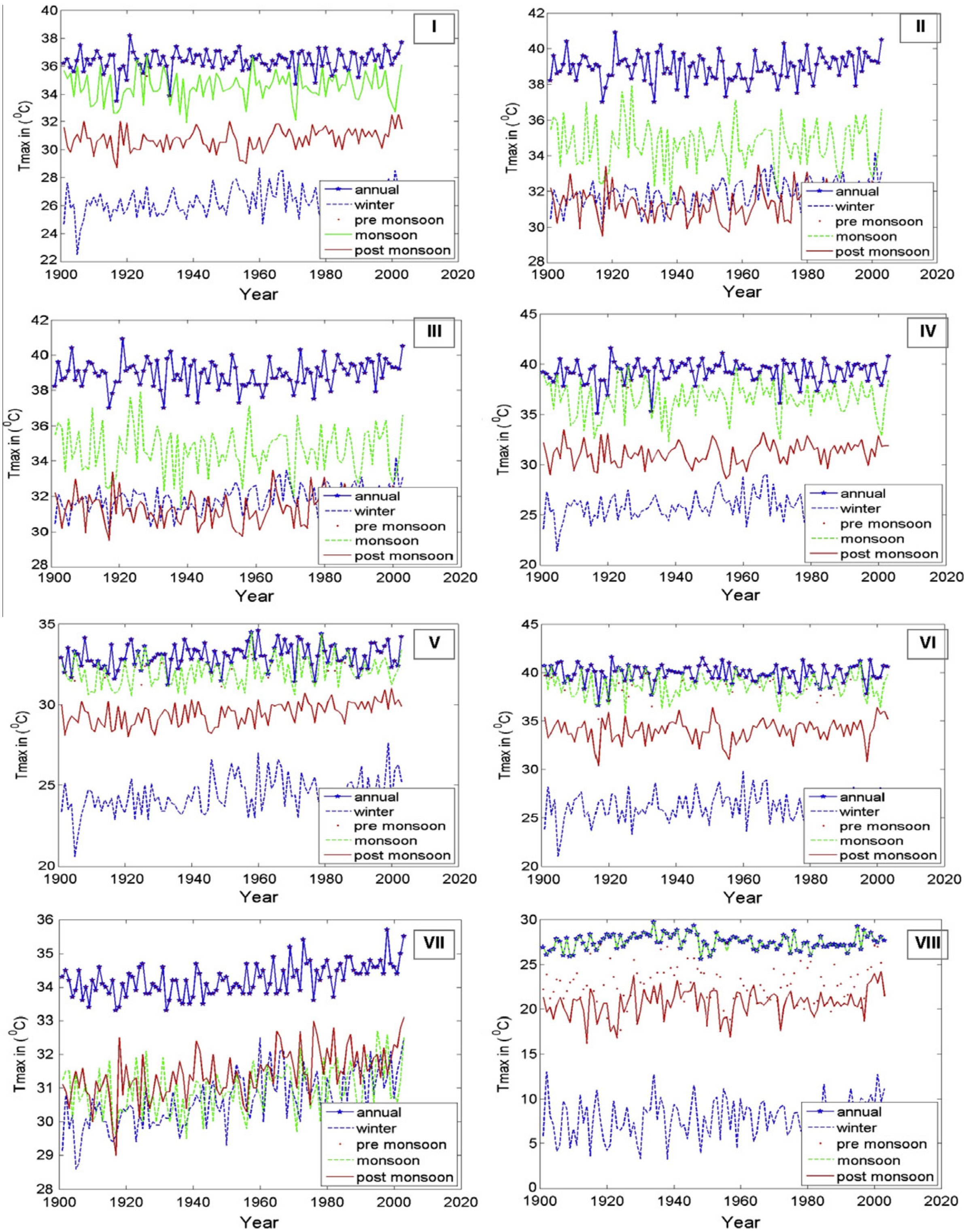

Fig. 2. Variation of maximum annual temperature (°C) across All India, temperature homogeneous regions viz. EC, IP, NC, NE, NW, WC, WH are given in plots I, II, III, IV, V, VI, VII, VIII respectively for the period 1901–2003.

ation. So its sequential behavior fluctuates around the zero level. The first step in this method is to find out n_j, number of time $x_j > x_i$ where x_i and x_j are the sequential values in a series. x_j ($j = 1, \ldots, n$) are compared with x_i ($i = 1, \ldots, j$). The test statistic t_j of SQMK test is calculated as

$$t_j = \sum_i^j n_j$$

The mean and variance of the test statistic t_j are $E(t) = \frac{n(n-1)}{4}$ and $Var(t_j) = \frac{\{j(j-1)(2j+5)\}}{72}$

After that $u(t_j)$ is calculated using

$$u(t_j) = \frac{t_j - E(t)}{\sqrt{Var(t_j)}}$$

In the same way $u'(t_j)$ is calculated starting from the end of the series.

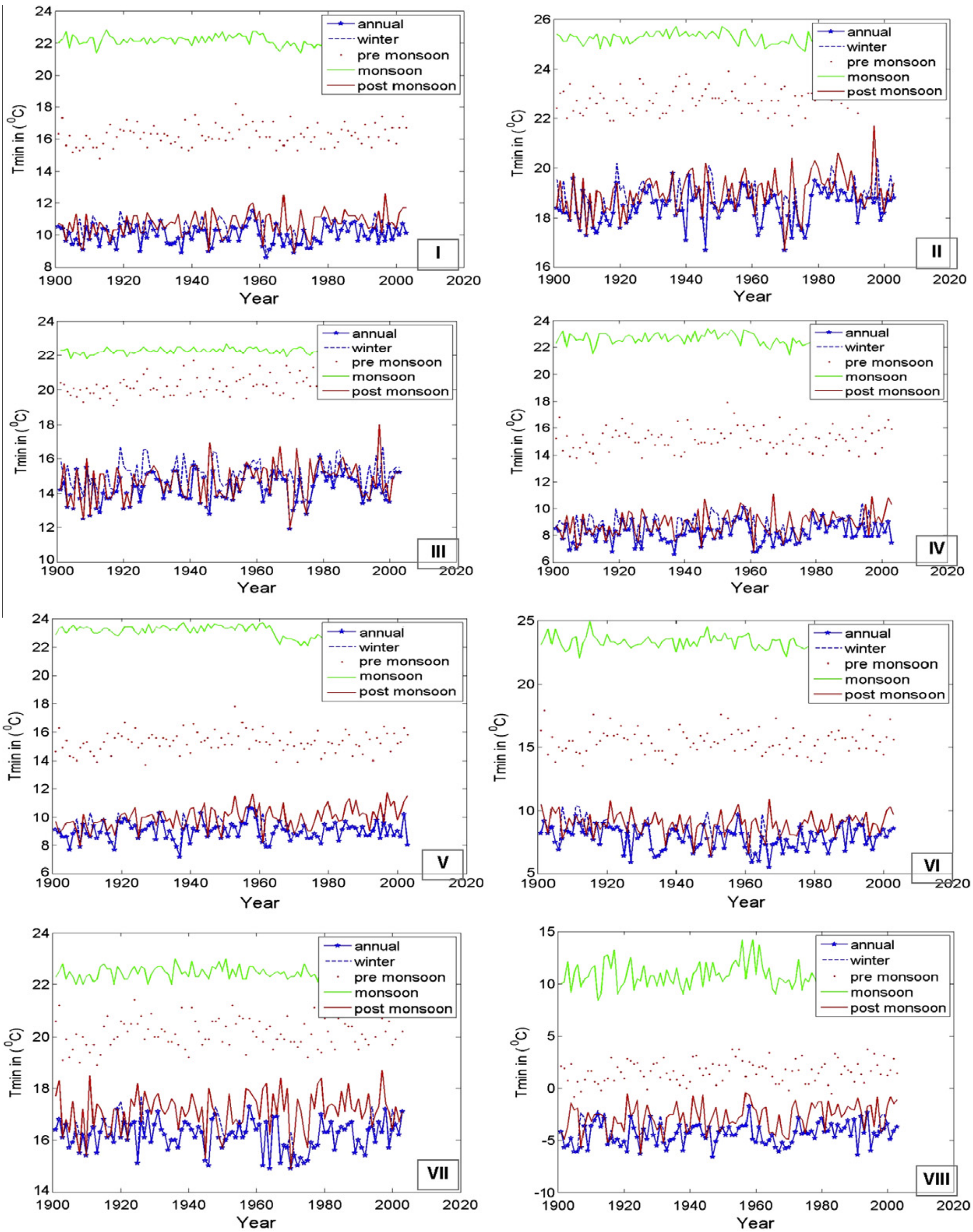

Fig. 3. Variation of minimum annual temperature (°C) across All India, temperature homogeneous regions viz. EC, IP, NC, NE, NW, WC, WH are given in plotsI, II, III, IV, V, VI, VII, VIII respectively for the period 1901–2003.

13. Innovative trend analysis technique (Sen, 2012)

This approach rests on the concept that if two time series are identical to each other, their plot against each other shows 45° straight line on the Cartesian coordinates irrespective of not holding good for all the assumptions in terms of distribution, sample length and serial correlation. If all the data points lie on 1:1 line, it means that there is no trend present in the time series. One important conclusion from the plot is that data values sort themselves in order along the 1:1 line. This idea is used in the trend detection by plotting the first half of the time series against the second half of the above mentioned idea. In innovative trend analysis technique, scatter points above or below the 1:1 line indicate increasing or decreasing monotonic trends respectively. If scatter

Table 1
Trend detection for All India maximum and minimum temperature in annual, monthly, winter, pre-monsoon, monsoon and post-monsoon levels, using MK, SR, MK-CF1, MK-CF2, TFPW and SS methods with three different periods viz. 1901–2003, 1948–2003, 1970–2003. In the table, '0' indicates no trend, '1' upward positive trend and '−1' downward trend. '–' sign & no sign before trend magnitude from SS method indicate negative and positive trends respectively.

Test	All India 1901–2003		All India 1948–2003		All India 1970–2003	
	t_{max}	t_{min}	t_{max}	t_{min}	t_{max}	t_{min}
Annual						
MK	0	0	0	0	0	0
SR	0	0	0	0	0	0
MK-CF1	0	0	1	0	0	0
MK-CF2	0	0	1	0	0	0
TFPW	0	0	0	0	0	0
SS (°C/year)	0.0030	0.0016	0.0062	0.0048	0.0158	0.0207
Monthly						
MK	1	0	0	0	0	0
SR	1	0	0	0	0	0
MK-CF1	1	0	1	0	0	0
MK-CF2	1	0	1	0	1	0
TFPW	1	0	0	0	0	0
SS (°C/month)	0.0006	0	0.0009	0	0.0015	0.0018
Winter						
MK	1	0	0	0	1	0
SR	1	0	0	0	1	0
MK-CF1	1	0	0	0	1	1
MK-CF2	1	0	0	0	1	1
TFPW	1	0	0	0	1	0
SS (°C/year)	0.0126	0	0.0062	0	0.0350	0.0181
Pre-Monsoon						
MK	0	0	0	0	0	0
SR	0	0	0	0	0	1
MK-CF1	0	1	0	0	0	0
MK-CF2	0	1	0	0	0	0
TFPW	0	0	0	0	0	0
SS (°C/year)	0.0036	0.0037	0.0063	0	0.0157	0.0200
Monsoon						
MK	0	0	0	0	0	1
SR	0	0	0	0	0	1
MK-CF1	0	0	0	0	0	1
MK-CF2	0	0	0	0	0	1
TFPW	0	0	0	0	0	1
SS (°C/year)	0.0023	0	0	0	0.0136	0.0181
Post-Monsoon						
MK	1	1	1	0	0	0
SR	1	1	1	0	0	0
MK-CF1	1	1	1	0	0	0
MK-CF2	1	1	1	0	1	0
TFPW	1	1	1	0	0	0
SS (°C/year)	0.0074	0.0069	0.0174	0.0100	0.0181	0.0222

points appear both sides, it specifies the presence of non monotonic increasing or decreasing trend hidden at different time scales in the same time series. Closer the scatter points to the 1:1 line, stronger the magnitude of trend and vice versa.

14. Data

Whole of India and seven temperature homogeneous regions as defined by Indian Institute of Tropical Management (IITM, Pune, source: http://www.tropmet.res.in) (Fig. 1) are considered in this study. The proposed formal trend detection analysis will be applied to all the seven temperature homogenous regions and India as a whole. The main motive for this study is to deduce broad inferences on the recent climate changes in India, which will be helpful in the later part to attribute these changes to specific contributing factors which are actually responsible for it.

There are three studies which explain the intense change in minimum temperature during last three decades in India viz. (Kothawale et al., 2010; Kumari et al., 2007; Kothawale and Rupa Kumar, 2005). These studies motivated us to look into the temporal variability of extreme temperatures in detail at different time steps viz. annual, monthly and seasonal during different time periods considered. In spite of small record length to detect and attribute the changes in the recent climate, consideration of last three decades is essential. Besides this, analysis of change in temperature extremes during entire 20th century as well as during the second half of the 20th century, it is also significant as 34 (1970–2003) years is the minimum number of years required for trend detection. Consideration of whole data sets i.e. the 20th century and second half of 20th century are essential to provide statistical significance to the inferences drawn using minimum record length (1970–2003) and to get the essence of likely possible causes for climate change during 20th century. In most of the literature, it is mentioned that during second half of 20th century rapid industrialization and acute green house gas emission commenced. It is also suggested in the literature that in India summer monsoon variability, surge in warming trend, highest temperature anomalies recorded during last three decades in global scale could be a clear impression of global warming.

Present study examines the trends in the temperature extremes (both maximum and minimum temperature) in yearly, monthly and seasonal basis. For detailed temporal changes in time series

Table 2
Trend detection for EC maximum and minimum temperature in annual, monthly, winter, pre-monsoon, monsoon and post-monsoon levels, using MK, SR, MK-CF1, MK-CF2, TFPW and SS methods with three different periods viz. 1901–2003, 1948–2003, 1970–2003. In the table,'0' indicates no trend,'1' upward positive trend and '−1' downward trend. '–' sign & no sign before trend magnitude from SS method indicate negative and positive trends respectively.

Test	EC 1901–2003		EC 1948–2003		EC 1970–2003	
	t_{max}	t_{min}	t_{max}	t_{min}	t_{max}	t_{min}
Annual						
MK	0	1	1	0	0	0
SR	0	1	1	0	0	0
MK-CF1	0	1	1	0	0	0
MK-CF2	0	1	1	0	0	0
TFPW	0	1	1	0	0	0
SS (°C/year)	0.0023	0.0047	0.0171	0.0046	0.0214	0.0077
Monthly						
MK	1	0	1	0	0	0
SR	1	0	1	0	0	0
MK-CF1	1	0	1	0	0	0
MK-CF2	1	0	1	0	0	0
TFPW	1	0	1	0	0	0
SS (°C/month)	0.0005	0.0002	0.0013	0.0004	0.0013	0.0013
Winter						
MK	1	0	1	0	1	0
SR	1	0	1	0	1	0
MK-CF1	1	0	1	0	1	0
MK-CF2	1	0	1	0	1	0
TFPW	1	0	1	0	1	0
SS (°C/year)	0.0099	0.0033	0.0152	0.0059	0.0250	0.0087
Pre-Monsoon						
MK	0	1	1	1	0	1
SR	0	1	1	1	0	1
MK-CF1	0	1	1	1	0	1
MK-CF2	0	1	1	1	0	1
TFPW	0	1	1	1	0	1
SS (°C/year)	0.0033	0.0067	0.0200	0.0122	0.0222	0.0250
Monsoon						
MK	0	0	0	0	0	1
SR	0	0	0	0	0	1
MK-CF1	0	0	0	1	0	1
MK-CF2	0	0	1	1	0	1
TFPW	0	0	0	1	0	1
SS (°C/year)	0	0	0.0051	0.0044	0	0.0173
Post-Monsoon						
MK	1	1	1	0	0	0
SR	1	1	1	0	0	0
MK-CF1	1	1	1	0	0	0
MK-CF2	1	1	1	0	0	0
TFPW	1	1	1	0	0	0
SS (°C/year)	0.0058	0.0068	0.0150	0.0053	0.0125	−0.0080

Table 3
Trend detection for IP maximum and minimum temperature in annual, monthly, winter, pre-monsoon, monsoon and post-monsoon levels, using MK, SR, MK-CF1, MK-CF2, TFPW and SS methods with three different periods viz. 1901–2003, 1948–2003, 1970–2003. In the table, '0' indicates no trend,'1' upward positive trend and '−1' downward trend. '–' sign & no sign before trend magnitude from SS method indicate negative and positive trends respectively.

Test	IP 1901–2003		IP 1948–2003		IP 1970–2003	
	t_{max}	t_{min}	t_{max}	t_{min}	t_{max}	t_{min}
Annual						
MK	0	1	1	0	1	0
SR	0	1	1	0	1	0
MK-CF1	0	1	1	0	1	0
MK-CF2	0	1	1	0	1	0
TFPW	0	0	1	0	1	0
SS (°C/year)	0.0032	0.0058	0.0214	0	0.0286	0.0100
Monthly						
MK	1	0	1	0	0	0
SR	1	0	1	0	0	0
MK-CF1	1	0	1	0	0	0
MK-CF2	1	0	1	0	0	0
TFPW	0	0	1	0	0	0
SS (°C/month)	0.0004	0.0003	0.0011	0	0.0011	0.0006
Winter						
MK	1	0	0	0	0	0
SR	1	0	0	0	0	0.
MK-CF1	1	0	1	0	0	0
MK-CF2	1	0	1	0	0	0
TFPW	1	0	0	0	0	0
SS (°C/year)	0.0100	0.0028	0.0085	0.0022	0.0152	0.0208
Pre-Monsoon						
MK	0	1	1	0	1	0
SR	0	1	1	0	1	0
MK-CF1	0	1	1	0	1	0
MK-CF2	0	1	1	0	1	0
TFPW	0	1	1	0	1	0
SS (°C/year)	0.0032	0.0074	0.0214	0.0077	0.0286	0.0071
Monsoon						
MK	0	1	0	0	0	1
SR	0	1	0	0	0	1
MK-CF1	0	1	0	0	0	1
MK-CF2	0	1	0	0	0	1
TFPW	0	1	0	0	0	1
SS (°C/year)	0	0.0022	0.0041	0.0019	0.0167	0.0083
Post-Monsoon						
MK	0	1	1	0	0	0
SR	0	1	1	0	0	0
MK-CF1	0	0	1	0	0	0
MK-CF2	0	0	1	0	0	0
TFPW	0	1	1	0	0	0
SS (°C/year)	0.0025	0.0071	0.0167	0.0028	0.0118	0

of extreme temperatures during 20th century, three different time slots are considered viz., 1901–2003, 1948–2003 and 1970–2003.

For the present study, a year is divided into four different seasons to conduct a detailed analysis of monthly and seasonal temperature. Thus the varieties of data considered in this study are yearly, monthly, Winter (JF), Pre-Monsoon (MAM), Monsoon (JJAS), and Post-Monsoon (OND). Time series of extreme temperatures i.e. monthly maximum temperature and monthly minimum temperature have been considered for India as a whole as well as the seven temperature homogeneous regions, viz., Western Himalaya (WH), Northwest (NW), Northeast (NE), North Central (NC), East coast (EC), West coast (WC) and Interior Peninsula (IP) (shown in Fig. 1).

15. Results and discussion

In this study it is analyzed how the maximum and minimum temperatures are varying for different parts of a year such as monthly, winter, pre-monsoon, monsoon, post-monsoon with respect to time for three different time periods viz. 1901–2003, 1948–2003 and 1970–2003. Due to lack of space, results for maximum and minimum temperature for All India and seven temperature homogeneous regions of India viz. EC, IP, NC, NE, NW, WC, and WH are shown in Figs. 2 and 3, only for the period 1901–2003.

Using Kolmogorov–Smirnov test (KS-test) all the data sets viz. annual, monthly, winter, pre-monsoon, monsoon, post-monsoon for the entire length (1901–2003) were checked. None of the data sets were following normal distribution. Hence analyzing trend detection using Least squares linear regression (LR) was dropped. A nominal level of significance of 0.05 is considered for all trend analysis techniques in this study.

MK test, SRC test, SS for trend magnitude, TFPW approach with MK, MK-CF1 and MK-CF2 tests have been applied to All India as well as the seven temperature homogeneous regions of India for maximum and minimum temperatures (t_{max}, t_{max}) at annual, monthly, winter, pre-monsoon, monsoon, post-monsoon levels for three defined time slots viz. 1901–2003, 1948–2003 and 1970–2003. Results are shown for All India and the seven temper-

Table 4
Trend detection for NC maximum and minimum temperature in annual, monthly, winter, pre-monsoon, monsoon and post-monsoon levels, using MK, SR, MK-CF1, MK-CF2, TFPW and SS methods with three different periods viz. 1901–2003, 1948–2003, 1970–2003. In the table,'0' indicates no trend,'1' upward positive trend and '-1' downward trend. '-' sign & no sign before trend magnitude from SS method indicate negative and positive trends respectively.

Test	NC 1901–2003		NC 1948–2003		NC 1970–2003	
	t_{max}	t_{min}	t_{max}	t_{min}	t_{max}	t_{min}
Annual						
MK	0	0	0	0	0	0
SR	0	0	0	0	0	0
MK-CF1	0	0	0	0	0	0
MK-CF2	0	0	0	0	0	0
TFPW	0	0	0	0	0	0
SS (°C/year)	0.0031	0.0042	−0.0037	0.0036	0.0036	0.0160
Monthly						
MK	0	0	0	0	0	0
SR	0	0	0	0	0	0
MK-CF1	1	0	0	0	0	0
MK-CF2	1	0	0	0	0	0
TFPW	1	0	0	0	0	0
SS (°C/month)	0.0006	0	0.0006	0	0.0011	0.0021
Winter						
MK	1	0	0	0	0	0
SR	1	0	0	0	0	0
MK-CF1	1	0	0	0	0	0
MK-CF2	1	0	0	0	0	0
TFPW	1	0	0	0	0	0
SS (°C/year)	0.0104	0	−0.0031	−0.0076	0.0281	0.0143
Pre-Monsoon						
MK	0	0	0	0	0	0
SR	0	0	0	0	0	0
MK-CF1	0	0	0	0	0	0
MK-CF2	1	0	0	0	0	0
TFPW	0	0	0	0	0	0
SS (°C/year)	0.0041	0.0042	−0.0037	−0.0023	0.0036	0.0259
Monsoon						
MK	0	0	0	0	0	1
SR	0	0	0	0	0	1
MK-CF1	0	0	0	0	0	1
MK-CF2	0	0	0	0	0	1
TFPW	0	0	0	0	0	1
SS (°C/year)	0	-0.0016	-0.0142	-0.0047	0.0125	0.0192
Post-Monsoon						
MK	1	1	1	0	0	0
SR	1	1	0	0	0	1
MK-CF1	1	1	1	1	1	1
MK-CF2	1	1	1	1	1	0
TFPW	1	1	0	0	0	0
SS (°C/year)	0.0088	0.0101	0.0167	0.0153	0.0167	0.0348

Table 5
Trend detection for NE maximum and minimum temperature in annual, monthly, winter, pre-monsoon, monsoon and post-monsoon levels, using MK, SR, MK-CF1, MK-CF2, TFPW and SS methods with three different periods viz. 1901–2003, 1948–2003, 1970–2003. In the table, '0' indicates no trend, '1' upward positive trend and '−1' downward trend. '−' sign & no sign before trend magnitude from SS method indicate negative and positive trends respectively.

Test	NE 1901–2003		NE 1948–2003		NE 1970–2003	
	t_{max}	t_{min}	t_{max}	t_{min}	t_{max}	t_{min}
Annual						
MK	1	0	0	0	0	0
SR	0	0	0	0	0	0
MK-CF1	0	0	0	0	0	0
MK-CF2	0	0	0	0	0	0
TFPW	1	0	0	0	0	0
SS (°C/year)	0.0053	0	0	0	0	0.0047
Monthly						
MK	1	0	0	0	0	1
SR	1	0	0	0	0	1
MK-CF1	1	0	0	0	0	1
MK-CF2	1	0	0	0	0	1
TFPW	1	0	0	0	0	0
SS (°C/month)	0.0007	0	0.0007	0	0.0009	0.0024
Winter						
MK	1	0	0	0	0	1
SR	1	0	0	0	0	1
MK-CF1	1	0	0	0	0	1
MK-CF2	1	0	0	0	0	1
TFPW	1	0	0	0	0	0
SS (°C/year)	0.0145	0	0.0042	-0.0080	0.02941	0.0067
Pre-Monsoon						
MK	1	0	0	0	0	1
SR	1	0	0	0	0	1
MK-CF1	1	0	0	0	0	1
MK-CF2	1	0	0	0	0	1
TFPW	1	0	0	0	0	1
SS (°C/year)	0.0068	0.0024	0	0	0	0.0250
Monsoon						
MK	1	−1	0	−1	0	1
SR	1	−1	0	−1	0	1
MK-CF1	1	−1	0	−1	0	1
MK-CF2	1	−1	0	−1	0	1
TFPW	1	−1	0	−1	0	1
SS (°C/year)	0.0074	−0.0048	0.0083	−0.0100	0.0100	0.0207
Post-Monsoon						
MK	1	1	1	0	0	1
SR	1	1	1	0	0	1
MK-CF1	1	1	1	0	0	1
MK-CF2	1	1	1	0	0	1
TFPW	1	1	1	0	0	1
SS (°C/year)	0.0125	0.0109	0.0150	0.0110	0.0150	0.0450

ature homogeneous regions of India in tabular form (from Tables 1–8).In the table, '0' indicates no trend, '1' upward positive trend and '−1' downward trend. Positive and negative trend magnitude obtained by SS method indicate the presence of same nature of trend.

As there is a good chance of monthly data having serial correlation and as BBS can take care of preserving serial correlation (resampling) present in the original observations, BBS-MK and BBS-SR are applied only for the monthly maximum and minimum temperature dataset. From the auto correlation plot, the least significant serial correlation, with respect to lag (k) was found. The optimized block length for each series was set to ($k + 1$). 10,000 bootstrap samples were generated. In most of the cases, optimized block length size is 8–10. Analysis is done for All India and the seven temperature homogeneous regions of India. Results for BBS-MK and BBS-SR are shown in Table 9 for both maximum and minimum temperatures, for all the considered time slots.

Next step is to find out the beginning of trend using sequential Mann–Kendall test. SQMK test has been applied to annual, winter, pre-monsoon, monsoon and post-monsoon extreme temperature series with the three different record lengths of 1901–2003, 1948–2003 and 1970–2003 in all the considered study areas. Sample results (post-monsoon maximum temperature of All India, EC, NC; annual maximum temperature of NE for the period 1901–2003 and monsoon minimum temperature of IP, NW, WC, WH for the period 1970–2003) are shown in Fig. 4.

Innovative trend analysis approach based on Sen (2012) is applied over all the regions considered for both the variables t_{max} and t_{min}, with different record lengths (1901–2002, 1948–2003 and 1970–2003). Instead of considering 1901–2003, we have considered 1901–2002 for our analysis, as both should be of equal numbers to plot the first half versus second half. Results shown in Tables 1–8 are matching with this trend detection result. Irrespective of the presence of serial correlation, this methodology is able to show the symptom of trend in terms of sub-series plots. So this method will give a clear picture of the preliminary analysis of any trend detection study. Due to space limitation, only a few results (annual maximum temperature for EC, IP; monthly maximum

Table 6
Trend detection for NW maximum and minimum temperature in annual, monthly, winter, pre-monsoon, monsoon and post-monsoon levels, using MK, SR, MK-CF1, MK-CF2, TFPW and SS methods with three different periods viz. 1901–2003, 1948–2003, 1970–2003. In the table, '0' indicates no trend, '1' upward positive trend and '-1' downward trend. '-' sign & no sign before trend magnitude from SS method indicate negative and positive trends respectively.

Test	NW 1901–2003		NW 1948–2003		NW 1970–2003	
	t_{max}	t_{min}	t_{max}	t_{min}	t_{max}	t_{min}
Annual						
MK	0	0	0	0	0	1
SR	0	0	0	0	0	1
MK-CF1	0	0	0	0	0	1
MK-CF2	0	0	0	0	0	1
TFPW	0	0	0	0	0	1
SS (°C/year)	−0.0016	−0.0042	0	0.0143	0.0143	0.0333
Monthly						
MK	0	0	0	0	0	0
SR	0	0	0	0	0	0
MK-CF1	0	0	0	0	0	0
MK-CF2	0	0	0	0	0	0
TFPW	0	0	0	0	0	0
SS (°C/month)	0.0004	−0.0001	0.0007	0	0.0023	0.0017
Winter						
MK	0	−1	0	0	0	1
SR	0	−1	0	0	0	1
MK-CF1	0	−1	0	0	0	1
MK-CF2	0	−1	0	0	0	1
TFPW	0	−1	0	0	0	1
SS (°C/year)	0.0079	−0.0073	0	0.0045	0.0384	0.0333
Pre-Monsoon						
MK	0	0	0	0	0	0
SR	0	0	0	0	0	0
MK-CF1	0	0	0	0	0	0
MK-CF2	0	0	0	0	0	0
TFPW	0	0	0	0	0	0
SS (°C/year)	0	0	−0.0042	−0.0023	0.0143	0.0238
Monsoon						
MK	0	0	0	0	0	0
SR	0	0	0	0	0	1
MK-CF1	0	0	0	0	0	1
MK-CF2	0	0	0	0	0	1
TFPW	0	0	0	0	0	0
SS (°C/year)	0	0	−0.0064	0	0.0400	0.0200
Post-Monsoon						
MK	0	0	1	0	0	1
SR	0	0	0	0	0	1
MK-CF1	0	0	1	0	1	1
MK-CF2	0	0	1	0	1	1
TFPW	0	0	1	0	0	1
SS (°C/year)	0.0054	0	0.0197	0.0133	0.0333	0.0347

Table 7
Trend detection for WC maximum and minimum temperature in annual, monthly, winter, pre-monsoon, monsoon and post-monsoon levels, using MK, SR, MK-CF1, MK-CF2, TFPW and SS methods with three different periods viz. 1901–2003, 1948–2003, 1970–2003. In the table, '0' indicates no trend, '1' upward positive trend and '−1' downward trend. '−' sign & no sign before trend magnitude from SS method indicate negative and positive trends respectively.

Test	WC 1901–2003		WC 1948–2003		WC 1970–2003	
	t_{max}	t_{min}	t_{max}	t_{min}	t_{max}	t_{min}
Annual						
MK	1	0	1	0	0	1
SR	1	0	1	0	1	1
MK-CF1	1	0	1	0	0	1
MK-CF2	1	0	1	0	0	1
TFPW	1	0	1	0	0	1
SS (°C/year)	0.0083	0	0.0131	0.0053	0.0125	0.0406
Monthly						
MK	1	0	1	0	1	0
SR	1	0	1	0	1	0
MK-CF1	1	0	1	0	1	0
MK-CF2	1	0	1	0	1	0
TFPW	1	0	1	0	1	0
SS (°C/month)	0.0010	0.0002	0.0013	0.0003	0.0019	0.0013
Winter						
MK	1	0	1	0	1	1
SR	1	0	1	0	1	1
MK-CF1	1	0	1	0	1	1
MK-CF2	1	0	1	0	1	1
TFPW	1	0	1	0	1	1
SS (°C/year)	0.0181	−0.0015	0.0141	0.0010	0.0357	0.0393
Pre-Monsoon						
MK	1	0	1	0	0	0
SR	1	0	1	0	1	0
MK-CF1	1	0	1	0	0	0
MK-CF2	1	0	1	0	0	1
TFPW	1	0	1	0	0	0
SS (°C/year)	0.0083	0.0019	0.0131	0	0.0125	0.0143
Monsoon						
MK	1	1	1	0	0	1
SR	1	1	0	1	0	1
MK-CF1	1	1	1	0	0	1
MK-CF2	1	1	1	0	0	1
TFPW	1	1	1	0	0	1
SS (°C/year)	0.0083	0.0025	0.0125	0.0050	0.0222	0.0143
Post-Monsoon						
MK	1	0	1	0	0	0
SR	1	0	1	0	0	0
MK-CF1	1	0	1	0	0	0
MK-CF2	1	0	1	0	1	0
TFPW	1	0	1	0	0	0
SS (°C/year)	0.0125	0.0030	0.0192	0.0053	0.0154	0

temperature for WC for the period 1948–2003 and monthly minimum temperature for NE; annual minimum temperature for NW, WC for the period 1970–2003) are shown in Fig. 5. In Fig. 5, first three and last three plots are for maximum and minimum temperatures respectively. All the scatter points appeared above and parallel to the 1:1 trend line excepting in plots III and IV which are for monthly time series. Plots III and IV could be a combination of both monotonic and non monotonic increasing trends at different hidden scales in the same time series. Other plots in Fig. 5 represent warming monotonic trend in case of both maximum and minimum temperature. In plots V and VI, stronger trend magnitudes are seen as compared to other plots. In case of plots I and II, scatter points closer to 1:1 line indicate weaker trend magnitude.

There is an agreement as well as disagreement between different methodologies implemented in this study. Specifically in many cases, trend is detected using MK-CF1 and MK-CF2. For example: all India annual and monthly maximum temperature during 1948–2003, NC post-monsoon maximum and minimum temperature during 1948–2003, NW post-monsoon maximum temperature during 1970–2003, WH annual and monsoon maximum temperature during 1970–2003 etc. Whereas in IP post-monsoon minimum temperature during 1901–2003, trend is detected using all methods excepting for MK-CF1 and MK-CF2. In some other cases, trend was found using MK-CF1, MK-CF2 and TFPW. For example: EC monsoon minimum temperature during 1948–2003, NC monthly maximum temperature during 1901–2003. Upon analyzing monthly time series, BBS-MK and BBS-SR approaches are comparable, but there are many disagreements between these and other approaches. For example: during the period 1970–2003 all India and EC minimum and maximum temperature, IP maximum temperature, NC minimum and maximum temperature, NW and WC minimum temperature except only one during 1901–2003 i.e. NW maximum temperature. In WH region there are disagreements in all the cases using resampling approach and other approaches used.

Based on the discrepancy among different techniques, it is significant to discern specific technique for trend detection in

Table 8
Trend detection for WH maximum and minimum temperature in annual, monthly, winter, pre-monsoon, monsoon and post-monsoon levels, using MK, SR, MK-CF1, MK-CF2, TFPW and SS methods with three different periods viz. 1901–2003, 1948–2003, 1970–2003. In the table,'0' indicates no trend,'1' upward positive trend and '−1' downward trend. '−' sign & no sign before trend magnitude from SS method indicate negative and positive trends respectively.

Test	WH 1901–2003		WH 1948–2003		WH 1970–2003	
	t_{max}	t_{min}	t_{max}	t_{min}	t_{max}	t_{min}
Annual						
MK	0	1	0	0	0	0
SR	0	1	0	0	0	0
MK-CF1	0	1	0	0	1	0
MK-CF2	0	1	0	0	1	0
TFPW	0	1	0	0	0	0
SS (°C/year)	0	0.0082	0.0028	0.0106	0.0200	0.0117
Monthly						
MK	0	0	0	0	0	0
SR	0	0	0	0	0	0
MK-CF1	0	0	0	0	0	0
MK-CF2	0	0	0	0	0	0
TFPW	0	0	0	0	0	1
SS (°C/month)	0.0006	0.0004	0.0019	0.0008	0.0039	0.0033
	Winter					
MK	1	0	1	0	1	0
SR	1	0	1	0	1	0
MK-CF1	1	0	1	0	1	1
MK-CF2	1	0	1	0	1	0
TFPW	1	0	1	0	1	0
SS (°C/year)	0.0232	0.0057	0.0500	0.0157	0.1000	0.0231
Pre-Monsoon						
MK	0	0	0	0	0	0
SR	0	0	0	0	0	0
MK-CF1	0	0	0	0	0	0
MK-CF2	0	0	0	0	0	0
TFPW	0	0	0	0	0	0
SS (°C/year)	0	0.0064	0.0200	−0.0013	0.0400	0.0231
Monsoon						
MK	0	0	0	0	0	1
SR	0	0	0	0	0	1
MK-CF1	0	0	0	0	1	1
MK-CF2	0	0	0	0	1	1
TFPW	0	0	0	0	0	1
SS (°C/year)	0	0.0029	0.0053	−0.0027	0.0200	0.0500
Post-Monsoon						
MK	1	1	0	1	0	0
SR	1	1	0	1	0	0
MK-CF1	1	1	0	1	0	0
MK-CF2	1	1	0	1	0	0
TFPW	1	1	0	1	0	0
SS (°C/year)	0.0111	0.0129	0.0211	0.0222	0.0467	0.0267

Table 9
Trend detection for All India, EC, IP, NC, NE, NW, WC and WH monthly maximum and minimum temperature using BBS-MK and BBS-SR methods with three different periods viz. 1901–2003, 1948–2003, 1970–2003. In the table, '0' indicates no trend, '1' upward positive trend and '−1' downward trend.

Methods	Region	1901–2003		1948–2003		1970–2003	
		Monthly temperature					
		t_{max}	t_{min}	t_{max}	t_{min}	t_{max}	t_{min}
BBS-MK	All India	1	0	1	0	1	1
BBS-SR		1	0	1	0	1	1
BBS-MK	EC	1	0	1	0	1	1
BBS-SR		1	0	1	0	1	1
BBS-MK	IP	1	0	1	0	1	0
BBS-SR		1	0	1	0	1	0
BBS-MK	NC	1	0	0	0	1	1
BBS-SR		1	0	0	0	0	1
BBS-MK	NE	1	0	0	0	0	1
BBS-SR		1	0	0	0	0	1
BBS-MK	NW	1	0	0	0	0	1
BBS-SR		1	0	0	0	0	1
BBS-MK	WC	1	0	1	0	1	1
BBS-SR		1	0	1	0	1	1
BBS-MK	WH	1	1	1	0	1	0
BBS-SR		1	1	0	0	1	0

observed data set. Even if some techniques are proved to be equally capable in trend identification, for example: MK and SR under idealized conditions, they may differ in real applications. Therefore it is always advisable to implement more than one technique. Possible causes for the disagreement between different methods are explained next.

Both MK and SR methods are comparable in detecting trend in almost all the cases considered for the present study. As both MK and SR methods failed to consider the effect of serial correlation in a time series, discrepancy is observed among methods i.e. MK, SR with MK-CF1, MK-CF2. In both the variance correction approaches i.e. MK-CF1, MK-CF2, proper care has been taken for both positive and negative correlations. TFPW also considers the effect of serial correlation under the assumption that time series follows AR (1) process. Though it is better than pre-whitening which affects the magnitude of slope, sometimes it has severe problem in maintaining important feature of statistical test i.e. nominal significance (Khaliq et al., 2009). MK and SR methods are inferior when the time series is serially correlated. Block bootstrapping approaches consider the serially correlated data block wise and seem to be more effective in detecting trend in case of monthly time series. Discrepancies are obtained mainly during the duration 1970–2003 between different methods while analyzing monthly time series. One possible reason could be the minimum length of record considered to conduct the trend detection study for this period. Other may be that the simulated dataset which generally finds the power of test theoretically may not always be same for the empirical dataset.

Mean annual temperature change of 0.22 °C/10 year is considered as substantial trend magnitude during the period 1971–2007 in literature (Kothawale and Rupa Kumar, 2005). Based on this, threshold of trend magnitude 0.022 °C/year is set to validate the present analysis. Almost all the significant trend magnitudes were observed during the last three decades. For example: all India post-monsoon minimum temperature and winter maximum temperature (1970–2003); EC winter temperature maximum and pre-monsoon temperature maximum and minimum (1970–2003); IP annual and pre-monsoon maximum temperature (1970–2003); NC winter temperature maximum and post-monsoon temperature minimum (1970–2003); NE winter maximum temperature, pre-monsoon and post-monsoon minimum temperature (1970–2003); NW annual, winter, pre-monsoon, post-monsoon temperature minimum and winter and monsoon, post-monsoon maximum temperature (1970–2003); WC annual and winter temperature minimum and winter and monsoon temperature maximum (1970–2003); WH winter and monsoon minimum temperature and pre-monsoon and post-monsoon both maximum and minimum temperature (1970–2003). Except last three decades, winter minimum temperature during 1901–2003 and post-monsoon maximum temperature during 1948–2003 in WH region are having significant temperature trends. During 1970–2003, in all the regions as well as in all India, increasing trend in monsoon minimum temperature has been obtained using almost all the methods.

On observing the results obtained from this study, shown in Tables 1–9 and Figs. 2–5, the following conclusions are made.

- Annual maximum temperature of All India for all the considered time periods except 1948–2003 are not showing any significant trend whereas regions WH, IP and EC are showing increasing trend for annual minimum temperature.

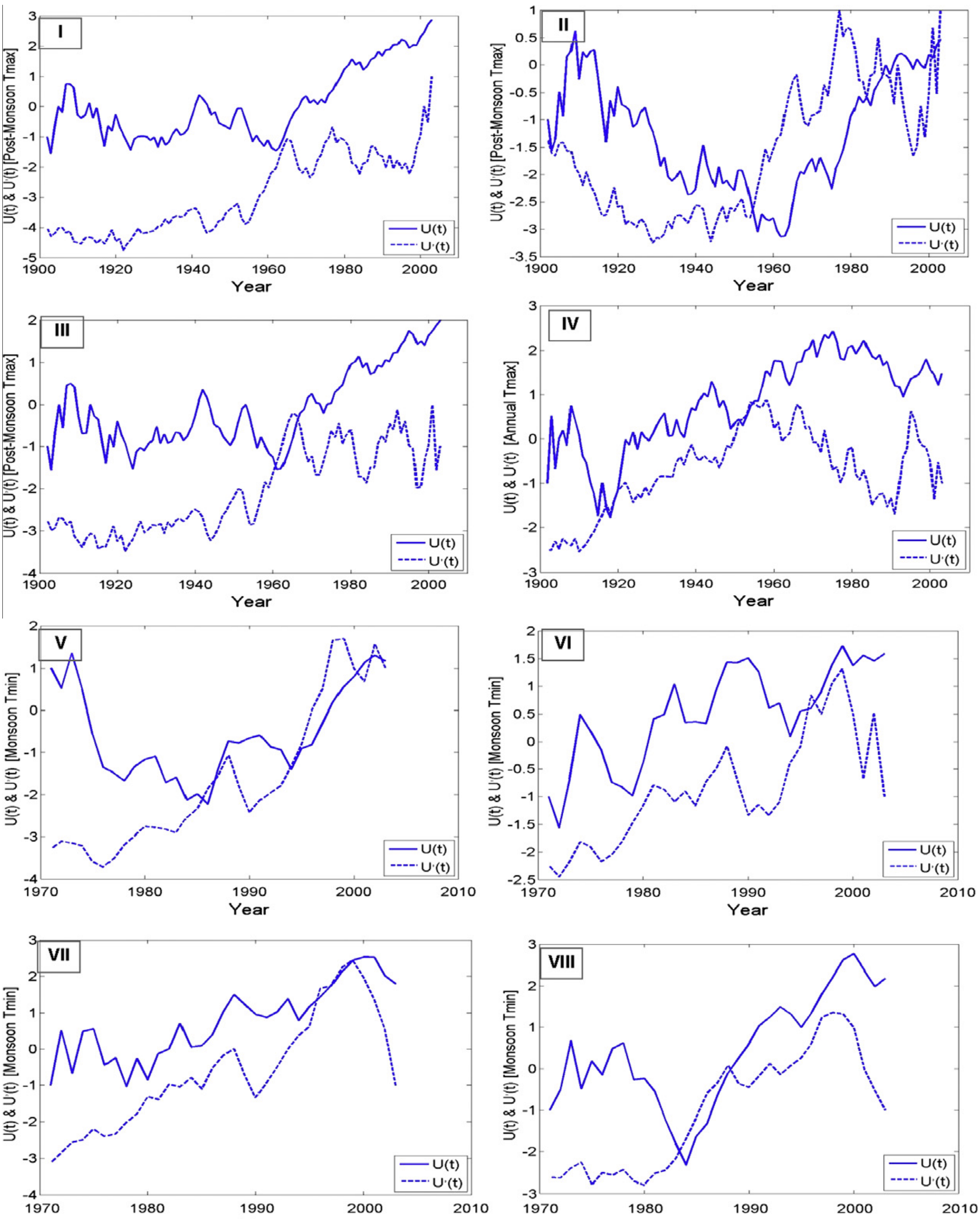

Fig. 4. Progressive and retrograde sequential values using SQMK test statistics u(t) and u'(t) for post-monsoon t_{max} of All India, EC, NC, annual t_{max} of NE for the period 1901–2003 and monsoon t_{min} of IP, NW, WC, WH for the period 1970–2003 are given in plots I, II, III, IV, V, VI, VII, VIII respectively.

- Monthly maximum temperature trend for the entire period (1901–2003) is seen in All India, EC, IP, NC, NE and WC regions, whereas minimum monthly temperature trend is not seen anywhere.
- Significant trend is found in winter maximum temperature for All India and six temperature homogeneous regions of India except NW (1901–2003), where as winter minimum temperature is showing downward trend only in NW region.
- Pre-monsoon maximum temperature is showing upward trend for NE and WC regions whereas minimum pre-monsoon temperature trend is significant in All India, EC and IP regions for the entire period.
- Monsoon maximum temperature trend is present in NE and WC regions and monsoon minimum temperature trend is present in IP, NE, WC regions for the entire considered period i.e. 1901–2003. Downward trend is seen in NE region.

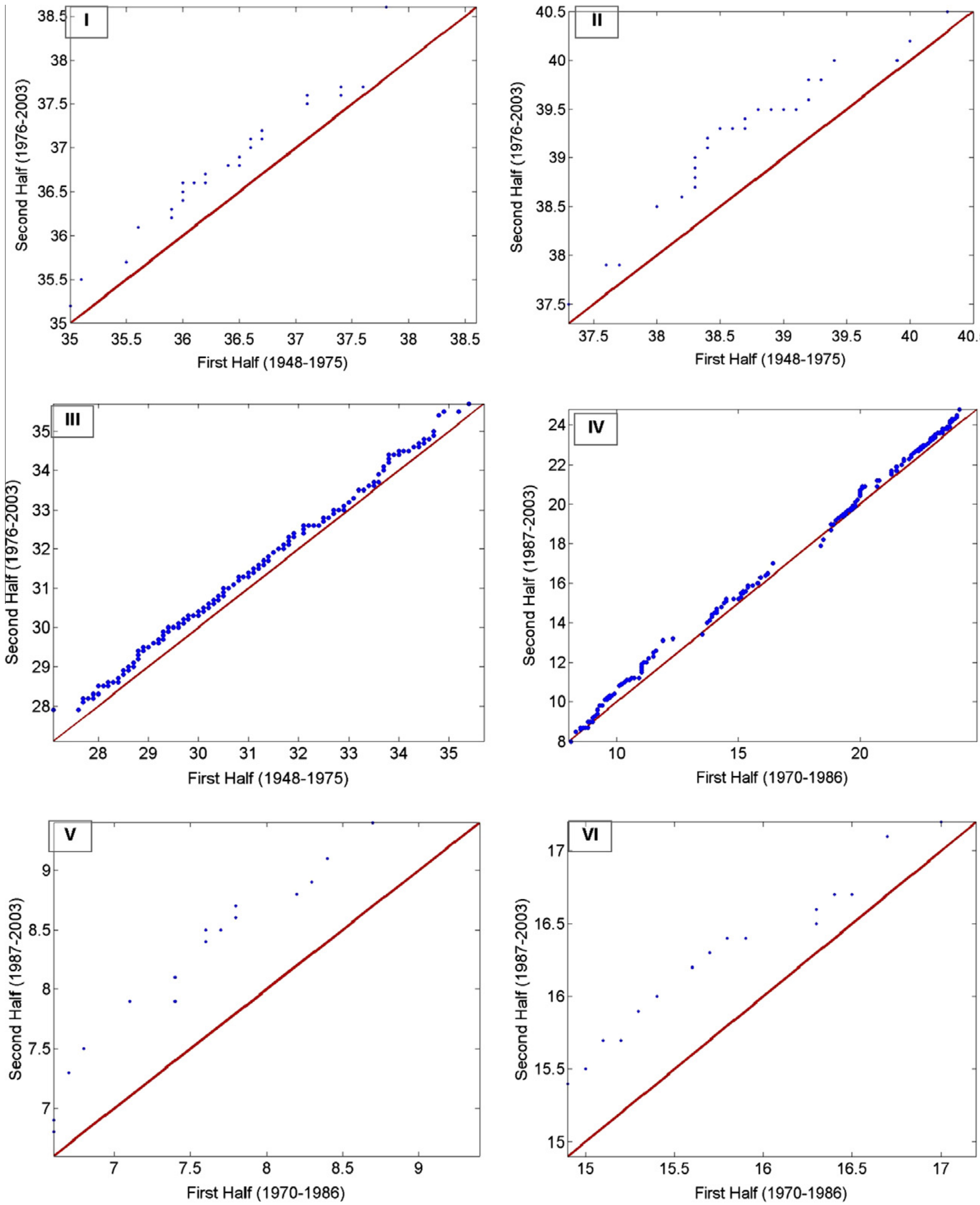

Fig. 5. Innovative trend detection technique's results for EC (t_{max}, annual), IP (t_{max}, annual), WC (t_{max}, monthly) for the period 1948–2003 and NE (t_{min}, monthly), NW (t_{min}, annual), WC (t_{min}, annual) for the period 1970–2003 are given in plots I, II, III, IV, V, VI respectively.

- Post-monsoon maximum temperature trend is found in All India, EC, NC, NE, WC and WH regions, whereas post-monsoon minimum temperature is significant in All India, EC, IP, NC, NE and WH regions for the time period (1901–2003).
- During the last three decades of 20th century, minimum temperature trend is found to be significant for the periods indicated:
  - All India during monsoon and winter.
  - EC during pre-monsoon and monsoon.
  - Both for IP and NC during monsoon.
  - NE during monthly, pre-monsoon, monsoon and post-monsoon.
  - NW during annual, winter, monsoon and post-monsoon.
  - WC during annual, winter and monsoon.
  - WH during monsoon.

- In All India level winter maximum temperature is significant for all the considered time slots except second half of the 20th century.
- In IP region during second half and last three decades of 20th century, trends are present in maximum annual temperature.
- Post-monsoon maximum and minimum temperature are showing positive trend for all the time periods in NC region.
- Both monthly and winter maximum temperature trend is present for all the time slots in WC region.
- Significant warming trend is found in monsoon minimum temperature during last three decades in all the temperature homogeneous regions as well as in all India. It is quite contrary for the whole duration i.e. 1901–2003. Similar conclusion was suggested by Kothawale and Rupa Kumar, 2005.
- Earlier studies suggest that the trend in minimum temperature is significant in the last three decades over India (Kothawale et al., 2010; Kothawale and Rupa Kumar, 2005; Kumari et al., 2007). This study concludes the above. Apart from this observation, it also suggests that the minimum temperature trend is significant in each temperature homogeneous region of India. It also testifies the presence of significant trend either at annual, monthly or seasonal level.

16. Conclusions

A set of seven temperature homogeneous regions of India along with All India were considered to detect trends in annual, monthly, winter, pre-monsoon, monsoon and post-monsoon maximum and minimum temperatures. A consistent increasing trend was detected in minimum temperature for most of the regions over India during the last three decades. Application of Sen's slope methodology also indicated that magnitudes of trend in most of the regions during last three decades are more intense for minimum temperature as compared to maximum temperature. In this way it agrees the statement that the difference between the day time high temperature and night time low temperature is decreasing in most parts of the World (Easterling et al., 1997; Kumari et al., 2007) along with India. During 20th century (1901–2003) significant maximum temperature trends were found in winter season for all the temperature homogeneous regions as well as in All India except NW region. Significant positive trends were found in post-monsoon maximum and minimum temperatures in NC region for all the considered time slots viz. 1901–2003, 1948–2003 and 1970–2003. During monsoon season of last three decades significant positive trend in minimum temperature is observed for the entire region. Annual maximum temperature for All India is showing significant trend only during the second half of 20th century.

In general, as the climate change and impact assessment analysis have not been looked in detail earlier for India, this study builds up for the first time, a full envision of recent temperature trends over India for different components (seasons) of a year during the same period of time for different regions using various methods. This detailed analysis will be useful to find out the likely influence of temperature change on hydrologic cycle, environmental resources and future water resources management of the country.

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